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LLNL-CONF-461316

Simulation of Infrared Laser Heating of Silica Using Heat Conduction and Multifrequency Radiation Diffusion Equations Adapted for Homogeneous Refractive Lossy Media

A. I. Shestakov, M. J. Matthews, R. M. Vignes, J. S. Stolken

October 29, 2010

MRS Spring Meeting
San Francisco, CA, United States
April 25, 2011 through April 29, 2011

LLNL-CONF-461316

Simulation of infrared laser heating of silica using heat conduction and multifrequency radiation diffusion equations adapted for homogeneous refractive lossy media*

A. I. Shestakov, M. J. Matthews, R. M. Vignes and J. S. Stölken
Lawrence Livermore National Laboratory
Livermore CA 94550

for presentation at: 2011 Materials Research Soc. Spring Mtg.

Abstract

Localized, transient heating of materials using micro-scale, highly absorbing laser light has been used in many industries to anneal, melt and ablate material with high precision. Accurate modeling of the relative contributions of conductive, convective and radiative losses as a function of laser parameters is essential to optimizing micro-scale laser processing of materials. In bulk semi-transparent materials such as silicate glass melts, radiation transport is known to play a significantly larger role as the temperature increases. Conventionally, radiation is treated in the frequency-averaged diffusive limit (Rosseland approximation.) However, the role and proper treatment of radiative processes under rapidly heated, high thermal gradient conditions, often created through laser-matter interactions, is at present not clear.

Starting from the radiation transport equation for homogeneous, refractive lossy media, we derive the corresponding time-dependent multifrequency diffusion equations. Zeroth and first moments of the transport equation couple the energy density, flux and pressure tensor. The system is closed by neglecting the temporal derivative of the flux and replacing the pressure tensor by its diagonal analogue. The radiation equations are coupled to a diffusion equation for the matter temperature. We are interested in modeling infrared laser heating of silica over sub-millimeter length scales, and at possibly rapid rates. Hence, in contrast to related work, we retain the temporal derivative of the radiation field. We derive boundary conditions at a planar air-silica interface taking account of reflectivities obtained from the Fresnel relations that include absorption. The effect of

*This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

a temperature-dependent absorption index is explored through construction of a multi-phonon dielectric function that includes mode dispersion. The spectral dimension is discretized into a finite number of intervals yielding a system of multigroup diffusion equations.

Simulations are presented. To demonstrate the bulk heat loss due to radiation and the effect of the radiation's temporal derivative, we model cooling of a silica slab, initially at 2500 K, for 10 s. Retaining the derivative enables correctly modeling the loss of photons initially present in the slab. Other simulations model irradiating silica discs (of approximately 5 mm radii and thickness) with a CO2 laser: $\lambda = 10.59$ and 4.6 um, Gaussian profile, $r_0 = 0.5$ mm for $1/e$ decay. By surrounding the disks in room-temperature air, we make use of the boundary conditions described above.